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MODELING AND SIMULATION OF ULTRASONIC SYSTEM

APURVA Y. GANDOLE, OMKAR S. GHATPANDE & TUSHAR R. JADHAV

Department of EnTC, V.I.I.T, Pune, Maharashtra, India

ABSTRACT

The Numerical simulations- i.e. the computers solved the problems by simulating theoretical models- is part of new technology has emerged long side pure theory and experiment during the last few decades. Computer simulations can bridge the gap between analysis and experiment. This paper provides modeling and simulation of ultrasonic system for material characterization. The system includes the transmitter, transmitting transducer, receiver, receiving transducer, material for characterization. This paper also provides the analogy between transducer and lossy transmission line. The use of PSPICE provides facility for simulation of complex set of excitation electronics, the ultrasonic transducer, the material under investigation, and the receiving electronics. Initially the analogy between transducer and lossy transmission line is discussed. The properties for lossy transmission lines were calculated for 5MHz transducer. Thus the velocity and attenuation for different materials is obtained. The experiment was successfully done and satisfactory results were obtained.

KEYWORDS: Simulation, Ultrasonic, Transducer

INTRODUCTION

The Numerical simulations- i.e. the use of computers to solve problems by simulating theoretical models- is part of new technology that has taken place along side pure theory and experiment during the last few decades. Numerical simulations help us to solve problems that may be hard for direct experimental study or complex for theoretical analysis *[Murawski 2002]*. Computer simulations can bridge the gap between experiment and analysis.

These simulations provide a new direction in ultrasonic measurements, of great importance to experiment and analysis. It has created a permanent position in every aspect of ultrasonic measurements. They are from basic research to engineering design. The computer experiment is a new and potentially powerful tool. By combining conventional theory, experiment and computer simulation, helps to view unsolved aspects of natural process. These aspects could often neither have been understood nor reveled by analysis or experiments alone. PSPICE is the derivative of the original SPICE program includes several added values such as graphical user interface and an enhanced plotting *[Tront 2004]*. Its widespread usage attests to the applicability of the program to large variety of circuit simulation problems. PSPICE utilizes modified nodal analysis approach. PSPICE can be used for non-linear dc, non-linear transient and linear ac analysis problems. It can also be used to perform noise analysis, temperature analysis, Monte-Carlo analysis. One of the advantages of PSPICE is its inclusion of device models for active and passive devices.

PSPICE simulators is used by engineers, designing a variety of applications including RF, Signal processing, Power supply etc *[Yadav et al 1991, Mancharkar et al 2005*

The success of modern electronics is due to the use of simulation tools which help to accurately predict system behavior. This example can be extended to components such as piezoelectric transducers attached to the electronics. The ability to simulate both piezoelectric transducer and electronics together renders effective optimizations at system level, i.e. minimizing size, cost and power consumption. In this paper the simulation of a combined electronics and ultrasonic piezoelectric transducer is explored. The environment used is compatible with the electronic simulation tool PSPICE. Improvement and verification of existing PSPICE models for ultrasonic equipment is described, and applied in the design of integrated analog electronics for an ultrasonic measurement system. Ultimately simulations are used to predict the response of a system without having to build it. From management point of view, it is done to save time and money as preliminary design have flaws. It is not feasible to have a scaled model; a mathematical model should lead to the right direction. In the case of ultrasound, a mathematical model makes much more sense.

DESIGN APPROACH

Block Diagram and Description

The block diagram Ultrasonic system is shown in figure 1. The high frequency pulse generator generates sharp radio frequency pulses of 5Mhzfrequenciy having pulse width 2 to 60 μs. The repetition rate of the pulses is 1 KHz. This high frequency pulse is fed to the ultrasonic transducer (Tx) having resonant frequency 5 MHz and 12 mm diameter. The receiver-transducer (Rx), which is at the other end of the sample, converts the received ultrasonic pulse into an electrical signal. This signal is fed to an amplifier and then detected.

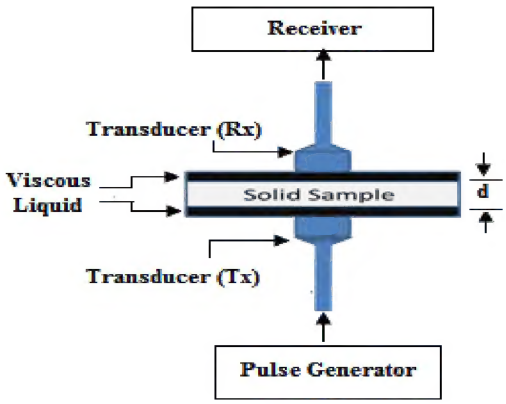


Figure 1: Block Diagram of Ultrasonic System

Pulser-Receiver System

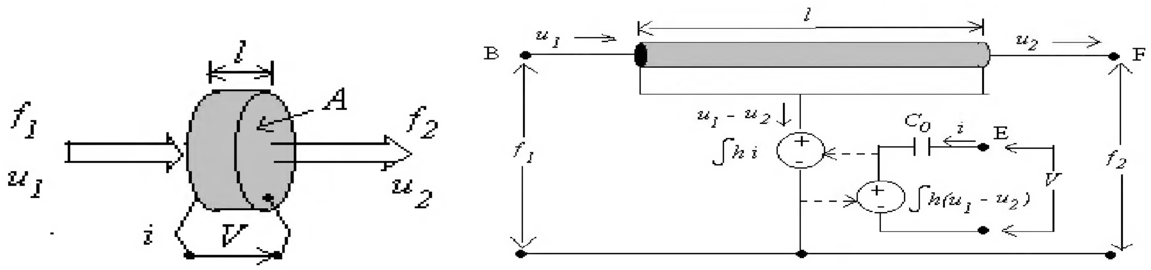
The transducer performs the conversion of electrical energy into mechanical energy, and conversely, the conversion of mechanical energy into electrical energy. The ultrasonic transmitting transducer transmits the high frequency sound waves through the moving material without direct contact, through the use of coupling medium i.e. the viscous liquid. The receiving transducer receives these ultrasound waves and then analysis is done on these waves. These waves when pass through the material under test, they get attenuated and require finite time to reach the receiving transducer. This time of flight is used to calculate the velocity. This attenuation and velocity is used for material characterization. There is a fundamental relationship between the properties of the transducer and the techniques have been developed for modeling transducer behavior and hence predicting the required system response.

Ultrasonic transducer usually consists of a piezoelectric element and non-piezoelectric layers for encapsulation

and acoustic matching. Points of interest are effects of backing materials, matching layers, piezoelectric materials, layer thickness, electrical matching and coupling on transducer characteristics like bandwidth, time response on different excitation signals and ring down behavior.

Wave Theory

The piezoelectric phenomena are modeled using controlled voltage and current sources *[Leach 1994].* Figure 2 (a and b) shows the scheme and controlled source equivalent circuit of the thickness-mode transducer respectively. Here in scheme (a) A is the cross sectional area, l is the thickness, f is the force, u is the particle velocity, V is the electrical voltage, i is the electrical current, h is the piezoelectric constant. The equivalent circuit consists of the static capacitance C_0 (capacitance between the electrodes), a transmission line which represents the mechanical part of the piezoelectric transducer and two controlled sources for coupling between the electrical and mechanical part of the circuit.



1(a) **1(b)**

Figure 2: Scheme (a) Transducer and (b) Equivalent Circuit for Piezoelectric Transducer

Suppose an ultrasonic pulse travels through a medium with a finite speed c (m/s). This pulse is refered as a disturbance. The medium reacts to this disturbance. Now for longitudinal wave, this disturbance is a compression or rarefaction of matter. The medium tries to displace so as to return to its equilibrium state. The compression and rarefaction within the medium is related to its density ρ (kg/m3), and the restoring force is related to the medium's bulk modulus M (Pa) *[Kinsler 1982].* Their relationship to the speed of sound is

$$c = \sqrt{\frac{M}{\rho}}$$

Now, an electrical pulse can travel through an electrical transmission line. These pulses are received at the other end of the line after a very short finite time. This time helps to give the velocity of these pulses. Analogous to the acoustic wave, the electrical pulses are concentrations and rarefaction of electrons within the transmission line *[Cheng, 1989].*

A lossy transmission line can be built with distributed-parameter network with the circuit parameters distributed throughout the line. One line segment with the length D x can be approximated with an electric circuit as in the figure 3.

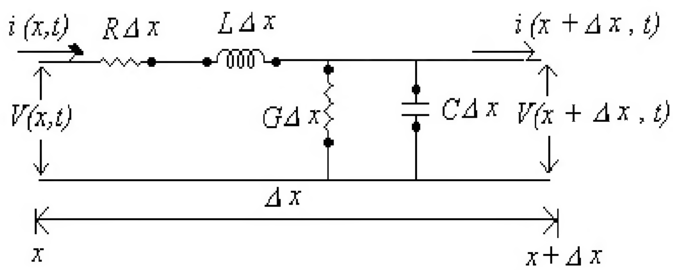


Figure 3: Equivalent Circuit of an Element of a Transmission Line with a Length of Δ x

This lossy transmission line model is described by four lumped parameters,

- *R* is the resistance in both conductors per unit length in W /m
- *L* is the inductance in both conductors per unit length in H/m
- *G* is the conductance of the dielectric media per unit length in ℧ /m
- *C* is the capacitance between the conductors per unit length in F/m

Where *R* and *G* is zero under loss less conditions.

To derive the parameters, applying Kirchhoff´s voltage law on the circuit in Figure 3:

$$V(x,t) - R\cdot\Delta x\cdot i(x,t) - L\cdot\Delta x\cdot\frac{\partial i(x,t)}{\partial t} - V(x+\Delta x,t) = 0 \tag{1}$$

Which can be written as:

$$-\frac{V(x+\Delta x,t)-V(x,t)}{\Delta x} = R\cdot i(x,t) + L\frac{\partial i(x,t)}{\partial t} \tag{2}$$

And then letting $\Delta x \rightarrow 0$ we get:

$$-\frac{\partial V(x,t)}{\partial x} = R\cdot i(x,t) + L\frac{\partial i(x,t)}{\partial t} \tag{3}$$

To get another equation relating *G* and *C*, applying Kirchhoff´s current law on the circuit (figure 2) we get:

$$i(x,t) - G\cdot\Delta x\cdot V(x+\Delta x,t) - C\cdot\Delta x\frac{\partial V(x+\Delta x,t)}{\partial t} - i(x+\Delta x,t) = 0 \tag{4}$$

And letting $\Delta x \rightarrow 0$ in equation (4) we get:

$$-\frac{\partial i(x,t)}{\partial x} = G\cdot V(x,t) + C\cdot\frac{\partial V(x,t)}{\partial t} \tag{5}$$

The first order partial differential equations, (3) and (5) are called the general transmission line equations. These equations can be simplified if the voltage *V(x, t)* and the current *i (x, t)* are time-harmonic cosine functions as:

$$V(x,t) = real(V'(x)\cdot e^{j\omega t}) \tag{6}$$

$$i(x,t) = real(I(x)\cdot e^{j\omega t}) \tag{7}$$

Where ω is the angular frequency Using equation (6) and equation (7), the general transmission line equations (3) and (4) can be written as:

$$-\frac{dV'(x)}{dx} = (R + j\omega L)\cdot I(x) \tag{8}$$

$$-\frac{dI(x)}{dx} = (G + j\omega C)\cdot V'(x) \tag{9}$$

These equations are called the time-harmonic transmission line equations. Equation (8) and equation (9) can be used to derive the propagation constant and the characteristic impedance of the line. By differentiating equation (8) and equation (9) with respect to *x*, we get:

$$\frac{d^2V'(x)}{dx^2} = \gamma^2 \cdot V'(x) \tag{10}$$

$$\frac{d^2I(x)}{dx^2} = \gamma^2 \cdot I(x) \tag{11}$$

Where γ is the propagation constant:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)\cdot(G + j\omega C)} \tag{12}$$

The real part α, of the propagation constant is called the attenuation coefficient in N p/m and the imaginary part, β, is called the phase constant of the line in rad/m.

The general solution to the differential equation (10) is

$$\mathrm{V'(x)} = \mathrm{A}\cdot e^{(\alpha+j\beta)x} + \mathrm{B}\cdot e^{(\alpha+j\beta)x} \tag{13}$$

The time dependence into the equation (13) can be obtained by multiplying $e^{j\omega t}$ to equation (13).

$$V''(x,t) = V'(x)\cdot e^{j\omega t} = A\cdot e^{-\alpha x}\cdot e^{j(\omega t-\beta x)} + B\cdot e^{\alpha x}\cdot e^{j(\omega t+\beta x)} \tag{14}$$

Equation (14) describes two traveling waves; one traveling in the positive *x* direction with an amplitude *A* which decays at a rate α while the other with an amplitude *B* travels in the opposite direction with the same rate of decay. The similar differential equations govern the acoustical wave propogation. In the case of harmonic waves, corresponding to equations (10) and (11), we have the lossy linearized acoustic plane wave equations

$$\frac{\partial^2 p(x,t)}{\partial x^2} + k_c^2 \cdot p(x,t) = 0 \tag{15}$$

$$\frac{\partial^2 u(x,t)}{\partial x^2} + k_c^2 \cdot u(x,t) = 0 \tag{16}$$

Where $p(x, t)$ (Pa) is the pressure and $u(x, t)$ (m/s) is the particle velocity *[Kinsleret al 1982]* equivalent to γ, k_c is the complex wave number composed of an attenuation constant α (N p/m) and a wave number *k* (rad/m). The general solution of the wave equation (15) is,

$$p(x,t) = Ae^{-\alpha x}e^{j(\omega t-kx)} + Be^{\alpha x}e^{j(\omega t+kx)} \tag{17}$$

And is identical to the solutions obtained in transmission line's represented by equation (14). Equation (16) has a

solution of the same form.

The complex wave number k_c is given as

$$k_c = \frac{\omega}{c}\frac{1}{\sqrt{1 + j\omega\tau}} \tag{18}$$

Where τ is the relaxation time *[Kinsleret al 1982]*

Using equations (17) and (18), we get

$$\alpha = \frac{\omega}{c}\frac{1}{\sqrt{2}}\sqrt{\frac{\sqrt{1+(\omega\tau)^2}-1}{\sqrt{1+(\omega\tau)^2}}} \tag{19}$$

And

$$k = \frac{\omega}{c}\frac{1}{\sqrt{2}}\sqrt{\frac{\sqrt{1+(\omega\tau)^2}-1}{\sqrt{1+(\omega\tau)^2}}} \tag{20}$$

In order to unify the two theories, an impedance type analogy is chosen. In this analogy the mechanical force is represented by voltage and current represents particle velocity. The characteristic impedance becomes important at the boundaries because at the boundaries continuity conditions have to be satisfied. Pressure and normal particle velocity must be continuous at the boundaries as voltage and current must be continuous at connections.

For the lossy transmission line *[Cheng, 1989]* the characteristic impedance Z_{el} is:

$$Z_{el} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{21}$$

And for the lossy acoustic medium *[Kinsleret al 1982]* the characteristic acoustic impedance Z_a is:

$$Z_a = \rho \cdot c \cdot \sqrt{1 + j\omega\tau} \tag{22}$$

Where ρ is the density of the medium

Expanding equation (21) and equation (12), we obtain,

$$Z_{el} \cong \sqrt{\frac{L}{C}}[1 + \frac{1}{2j\omega}(\frac{R}{L} - \frac{G}{C})] \tag{23}$$

And

$$\gamma \cong \frac{1}{2}\sqrt{LC}(\frac{R}{L} + \frac{G}{C}) + j\omega\sqrt{LC} \tag{24}$$

Considering small but non-negligible losses where R <<ωL, G <<ωC and ωτ<< 1, the second term of equation

(4.23) is negligible, leaving the characteristic impedance as $\sqrt{\frac{L}{C}}$ Similarly from equation (22), the low loss acoustical characteristic impedance can be approximated as ρc. Also, the wave number k from equation (20) become ω/c.

To correlate the two characteristic impedances, impedance type analogy is used (Figure 1 b), here the force, (not pressure) is represented by voltage and current represents the particle velocity. Thus the equivalence between the two systems is

$$Z_{el} \cong Z_a \cdot A \tag{25}$$

Where A (m^2) is the cross-sectional area of the acoustic beam. Refering the definition of the low loss characteristic impedances equation, following relationships can be obtained

$$L = A \cdot \rho \tag{26}$$

$$C = \frac{1}{A \rho c^2} \tag{27}$$

The real part of equation (24) is the attenuation coefficient α

$$\alpha = \frac{1}{2}\sqrt{LC}\,(\frac{R}{L}) + \frac{1}{2}\sqrt{LC}\,(\frac{G}{C}) \tag{28}$$

Drawing a parallel with the classical theory of acoustic attenuation, $\alpha_{classical} = \alpha_v + \alpha_{tc}$

Where is the coefficient of attenuation due to viscous losses and α_{tc} is the coefficient of attenuation due to thermal conduction From equations (26), (27) and (28), we can solve for R and G to model the attenuations such that,

$$R = 2\rho c A \alpha_v \tag{29}$$

$$G = \frac{2\alpha_{tc}}{\rho c A} \tag{30}$$

Because the materials layers used in this work have a low heat conductance, the loss due to thermal conduction is negligible, and we let the conductance G = 0.Equations (26), (27), (29) and (30) are the final equations required for simulation purpose.

Simulation Design

Piezoelectric Transducer

The model developed for piezoelectric transducer (Tx) (is shown in figure 4) The block T_1represents the transmission line. Independent sources V_1 and V_2 are zero value sources, which are used as ammeters in the circuit. F_1 and F_2 are dependent current sources. The value of F_1 is given by $F_1 = h\ C_0 \times I\ (V_1)$, where $I\ (V_1)$ is the current through V_1. The voltage across the dependent voltage source E_1 is given by $E_1 = V\ (4)$, where $V\ (4)$ is the voltage at node 4 i.e. the voltage across C_1. The dependent current source F_2 which charges C_1 is given by $F_2 = h \times I(V_2)$, where $I(V_2)$ is the current through V_2 and h is the ratio of the piezoelectric stress constant in the direction of propagation and the permittivity with

constant strain

Resistor R_1 is included to prevent node 4 from being a floating node. From the mechanical side (i.e. transmission line T1), the difference between the velocity of each surface normal to the propagation path, represented by the currents u_1 and u_2 controls the current source F_1. The same transducer is modeled for receiving transducer (Rx). The piezoelectric material PZT-5A whose material data was obtained from *[Berlincourt[a] et al (2001)]* and *[Kino[b] (1988)]*, was chosen and given in table 1

Table 1: Physical Properties of Transducers at 25 ° C

S No	Physical Properties at 25^{0}C	PZT-5A
1	Density (ρ) (kg/m^3)	7750 (b)
2	Mechanical Q (Q_m)	75 (b)
3	Sound velocity (c) (m/s)	4350 (b)
4	Permitivity with constant strain (ε^s) ($C^2/Nm^{2)}$	7.35 ×10^{-9} (b)
5	Piezoelectric stress constant (e^{33}) ($C/m^{2)}$	15.8 (b)
6	Acoustic Impedance (MRayl)	33.7 (b)
7	Piezoelectric Constant (10^{-12} C/N)	d_{33} = 374 (a) d_{15} = 584 (a)
8	Couping factor (K_{33})	0.66 (b)

To evaluate the model, the model parameters of Quartz crystal and PZT-5A transducers were calculated using equations (26, 27, 31, 32, 33, 35) and given in table 2.

Table 2: Model Parameters of Transducers

S No	Model Parameters	PZT-5A
Physical Parameters		
1	Diameter (mm)	12.7
2	Cross sectional area (A) (m^2)	0.0001267
3	Center frequency (MHz)	5MHz
Equivalent Lossy Transmission Line Parameters (Mechanical Section)		
4	C	53.8nF
5	R	411kΩ
6	L	981mH
7	G	0
8	len	435μm
Electrical Section Parameter		
9	Static capacitance C_0	2.14nF
Controlled Sources Parameter		
10	Transmitting constant (h) (N/C)	2.15× 10^9
11	Current source gain (F_2)	2.15× 10^9
12	Dependant current source gain (F_1)	4.60
13	Voltage control voltage source gain (E_1)	1
14	R_1	1 KΩ
15	C_1	1F

The measuring cell is modeled using lossy transmission line. To verify the analogies described above, experimental validation for solids are performed. To model a lossy acoustic layer as an electrical transmission line, the materials data i.e. the acoustic beam cross sectional area A (m^2), the density ρ (Kg/m^3), the speed of sound (m/s) and the attenuation constant α (N p/m) at the chosen frequency and temperature is needed as per equations 26, 27, 29 and 30. Hence the materials data was obtained from standard references; Lid e[(a)] (1999), Kaye[(b)]*et al* (1995) , Stewart[(c)]*et al* (1930),

Greenspan[d] *et al* (1959), Carl[e], W east [f] (1981), A say[g] *et al* (1967)are given in table3.

Table 3: Physical Properties of Sample Materials at 25° C

Materials (Liquids)	Density ρ (Kg/m^3)	Sound Velocity v (m/s)	Viscosity H (c P)	Acoustic Impedance Z (M Ray l)	Reference			
					ρ	v	η	Z
Distilled water	1000	1497	0.890	1.494	f	d	e	f
Materials (Solid)	**Density P (Kg/m^3)**	**Sound Velocity v, (m/s)**	**Young's Modulus E, (10^9 N/m^2)**	**Acoustic Impedance Z, (M Ray l)**	**Reference**			
					ρ	v	Y	Z
Teflon	2140	1390	0.5	2.97	a	g	a	a
Aluminium	2700	5100	69	17.33	a	c	a	a
Steel	7860	5874	200	46.00	b	c	b	b

Model parameters of some sample materials and intermediate layer are calculated using the dimensions of measuring cell, materials data and assigns to equivalent lossy transmission line T-intermediate layer and T-sample. Model parameters of the some sample materials are calculated at 25 °C using equations 26, 27, 29 and 30, which are given in table 4.

Table 4: Model Parameters of Some Solid Sample Materials at 25 °C

Frequency		5 MHz			
Model Parameters		C	L	R	G
S No	Material	µF	mH	KΩ	℧
1	Distilled water	3.52	126.7	0.208	0
2	Teflon	1.88	271	326	0
3	Aluminium	0.071	342	1.74	0
4	Steel	0.029	988	57.3	0

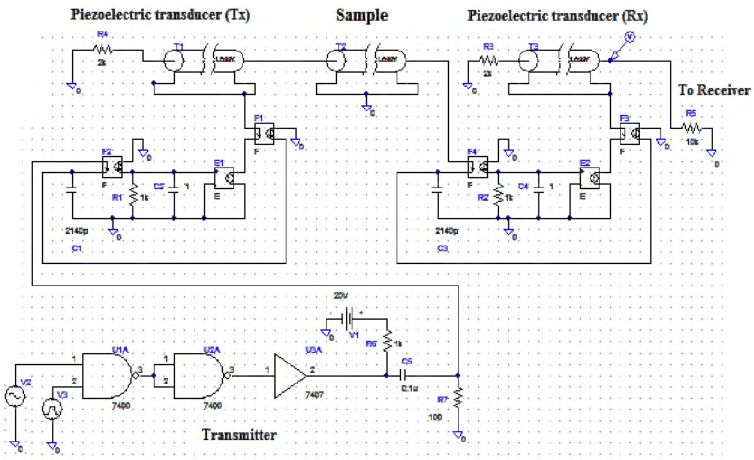
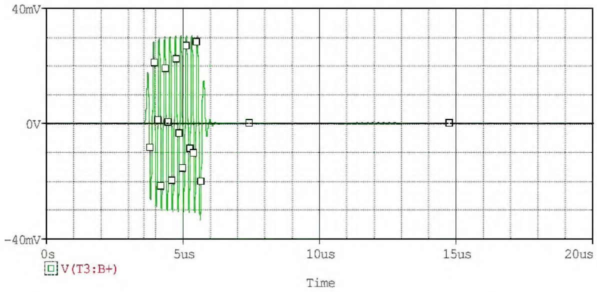


Figure 4: Simulation Circuit

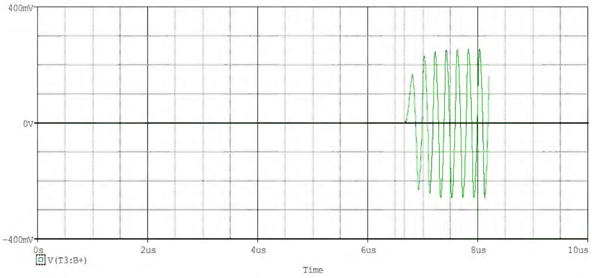
Analysis

Time Domain: The received signals from simulations in the time domain. Starting with solid samples, Figure 5, a and b shows the first 20µS received by the 5MHz transducers with a solid sample (Teflon) and Liquid sample (Distilled water) at 25 °C



A1: (3.5689u, 0.000) A2: (0.000, 0.000) DIFF (A): (3.5689u, 0.000)

Figure 5 (a): Complete Transient Received by 5 MHz Transducer at 25°C in Teflonat d=0.005m



A1: (6.6781u, 250.272mV) A2: (0.000, 0.000) DIFF (A): (6.6781u, 250.272mV)

Figure 5 (b): Complete Transient Received by 5 MHz Transducer at 25°C in Distilled Water at d=0.01m

Attenuation Measurement

Experimentally, the attenuation in each sample is based on measurement of pulse height of received signal by varying the distance between two transducers. The same procedure can be applied to the simulation by changing the *len* parameter (equivalent to distance in experimental method) of T sample model of measuring cell. Figure 6 shows the probe screen for measurement of pulse height using probe cursor. The received signal in distilled water at 25 °C using 5MHz transducer reflects the maximum pulse height 250.272mV with time of 6.6781u s. Similarly the remaining samples were tested and the results are compared with the experimental values, as shown in table 5 (a & b). The results clearly indicate that the simulation of an ultrasonic sensing device, including both electronic circuits and transducer is, possible using PSPICE. The major obstacle in applying this as a general method for ultrasound transducer prediction is the lack of appropriate materials data. This is especially pronounced when looking for temperature and frequency dependency of these data.

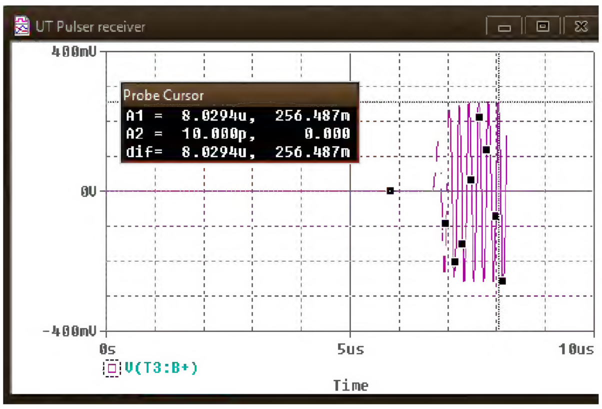


Figure 6: Probe Screen for Measurement of Pulse Height Using Probe Cursor

Table 5(a): Comparison of Ultrasonic Velocities in Liquid and Solid Samples at 25°C

S No	Sample	Simulated Velocity (m/s)	Literature Value(m/s)	Reference
1	Distilled water	1497.431	1497	Weastet *al* 1964
2	Aluminium	5143.999	5140	Podesta 2002
3	Steel	5870.105	5874	Kaye *et al* 1995
4	Teflon	1398.925	1400.31	Yawaleet *al* 1995
5	Copper	4750..470	4756	Kaye *et al* 1995

Table 5(b): Comparison of Ultrasonic Attenuation in Liquids and Solids Samples at 25°C

S No	Materials	Attenuation at 25 °C (2MHz)(α/f^2) $\times10^{-15}$ (N p m^{-1} Hz^2)		Reference
		Simulated	Literature	
1	Distilled water	23.100	22	Weast 1964
Solid Samples		Attenuation (dB/m)		
		Simulated	Literature	
2	Aluminium	1.199	1.151	Kaye *et al* 1995
3	Steel	6.577	5.600	Kaye *et al* 1995
4	Teflon	0.0048	0.0039	Lide 1999

CONCLUSIONS

Analogy between acoustic media and transmission lines is reviewed and an analogous electrical model using controlled sources of an ultrasonic transducer is discussed. A presentation of Simulation model of a complete ultrasonic system is done. The comparison between received signal from the simulation and that of an actual measurement in the time domain is done. This shows that temperature and frequency dependent parameters which are relevant to acoustic wave propagation can be modeled. The feasibility can be demonstrated in an ultrasound transducer setup for materials property investigation. Comparisons were made for attenuation and velocity of sound for organic liquids and solids. For these materials, the agreement is good. The simulation tool provides a way for prediction of the received signal before anything is built. Moreover, an ultrasonic simulation package used helps to amplify and process the received ultrasonic signals. This in turn provides for the development of the associated electronics. Such a virtual design and testing procedure saves time and money, and also provides better understanding of design failures and allows modification of designs more efficiently and economically.

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